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Rectennas for Thermal-Energy Conversion

Yi Pan, Catrin V. Powell, and Claudio Balocco
School of Engineering and Computing Sciences, Durham University, Durham, DH1 3LE, UK

***Abstract*—We demonstrated the conversion of thermal energy in the form of far- and mid-infrared using a micro rectenna, consisting of a spiral antenna coupled to an ultra-fast nanodiode, the so-called self-switching device (SSD). A maximum efficiency of 0.02 % was measured at a 973 K (700 °C) using a calibrated black-body radiator illuminating the rectenna. The relatively low efficiency was due to the impedance mismatch between the diode and the antenna, and can be reduced by designing a suitable matching structure. The fabrication of larger rectenna array could be exploited, for example, to harvest wasted thermal energy from exhaust pipes and industrial machinery.**

I. Introduction

Every hot object radiates energy in the form of electromagnetic radiation, with an intensity proportional to the fourth power of its temperature, as stated by the Stefan-Boltzmann law. Exhaust pipes and industrial machinery typically generate a large amount of thermal energy. However this is often lost, due to technological challenges in its conversion into some useable form. Some success has been reported using thermoelectric devices, but apart from being bulky, they require rare materials, such as bismuth telluride (Bi_2Te_3), which might pose environmental risks.

A different approach consists in collecting infrared radiation using a micro antenna, which deliver and ac electric signal to a diode which converts it to dc power. This device, called a rectenna, was proposed by Bailey in the early 70's for direct conversion of sunlight [1], as an alternative to solar cells. However, difficulties in the fabrication of diodes operating at such high speeds hampered its development. Moreover, the rectification mechanisms are not well understood, since rectennas driven by thermal sources behave as Brownian ratchets, rather than conventional rectifiers. This –combined to the practical difficulties in device characterization at infrared frequencies– makes the optimization of their parameters elusive.

Here we demonstrate the conversion of radiant thermal-energy with a rectenna at room temperature, illuminated by a black-body source with variable temperature.

II. Experimental Results

Our rectennas consisted of a broad-band self-complementary spiral antenna connected to a planar nanodiode, the so-called self-switching diode (SSD), located at the antenna feed point. The SSD was fabricated by etching an asymmetric nanochannel into a two-dimensional electron gas (2DEG) embedded in GaAs, using two L-shaped trenches. Details on the SSD fabrication and operation can be found in our previous works [2, 3]. The spiral antenna was later deposited onto the device, its arms providing electrical connection to the SSD. The spiral outer radius and feed gap were 600 μm and 5 μm, respectively, resulting in a cut-off frequency of approximately 6 THz. The rectenna, maintained at room temperature (296 K) was illuminated by a calibrated black-body source, whose temperature ranged from 300 °C to 700 °C (approx. 573 K□973 K).

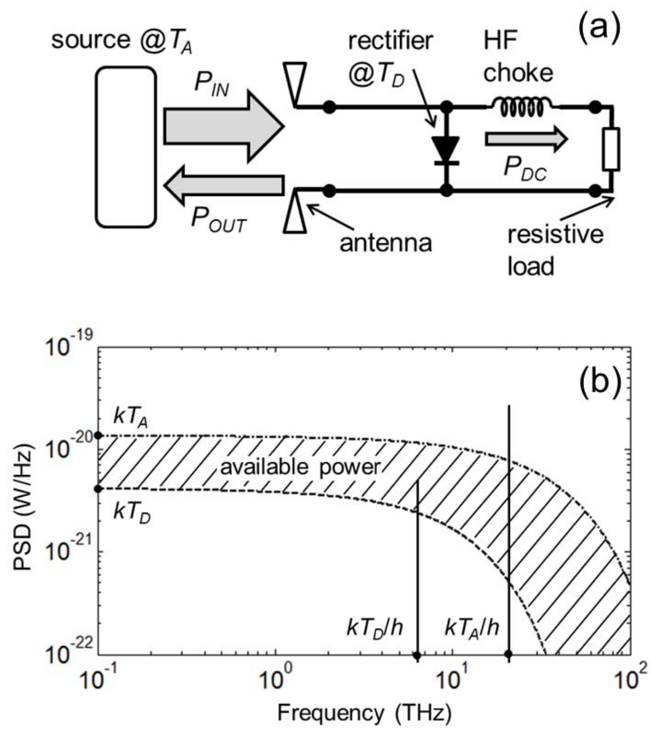

Fig. 1. (a) Rectenna circuit model. The input power P_{IN} is black-body radiation emitted by the source and collected by the antenna, while P_{OUT} is the power lost by the rectifier at a finite temperature. (b) Power spectral density (PSD) of P_{IN} and P_{OUT} at the antenna feedpoint. The hatched area is the maximum available power available for conversion. T_A = 973 K and T_D = 296 K, the quantum cutoff kT/h is shown in the graph.

Figure 1(a) shows a sketch of the rectenna circuit and thermal source. Assuming that the thermal source at the temperature T_A covers the entire field of view of the antenna, it appears at the antenna feed point with a Johnson-Nyquist power spectral density (PSD), and it thus equivalent to a resistor at a temperature T_A, providing an overall input power P_{IN}, as shown in Fig. 1. In order to calculate the maximum power available for conversion, the power lost through radiation due to the thermal fluctuation in the rectifier P_{OUT} has to be included, which also has a Johnson-Nyquist PSD. The power conversion P_{DC} is thus the result of the rectification of these thermal fluctuations, which can be studied in the framework of Brownian ratchets. The dc power is then delivered to a resistive load through an HF choke, which prevent radiation from leaking outside the rectenna structure. In our device the HF choke consists of narrow leads (nominally 10 μm wide) connected to the edges of the spiral antenna. The sharp discontinuity between the antenna and leads is enough to provide efficient choking. It is interesting to note that a thermal rectenna is an electrical equivalent of the well-known Feynman's ratchet and pawl device [4], and both systems can be studied using the same model [5].

The overall available power, shown graphically in Fig. 1(b) with the hatched area, is [6]:

$$P_{AV} = P_{IN} - P_{OUT} = \frac{\pi^2 k^2}{6h}({T_A}^2 - {T_D}^2), \quad (1)$$

where k is the Boltzmann's constant and h the Planck's constant. The conversion efficiency η can then be calculated once the dc power P_{DC} is measured as:

$$\eta = P_{DC}/P_{AV} \quad (2)$$

Figure 2 shows the short-circuit current I_{SC} and the open-circuit voltage V_{OC} as a function of the source temperature T_A. The maximum rectified dc power P_{DC} was determined by loading the rectenna with a variable resistance, which resulted in the expected fill factor of approximately 25 %. The maximum experimental efficiency was approximately 0.02% with a source temperature of 973 K. However, the thermodynamic efficiency, while still limited by the Carnot's efficiency, is expected to be much larger; the impedance mismatch between the antenna (approx. 200 Ω) and the diode (approx. 3 MΩ), resulted in a large fraction of the power to be reflected back to the antenna, largely reducing the available power P_{AV} and consequently the efficiency. A measurement campaign using a THz vector network analyzer is in progress to characterize precisely the reflection coefficient due to this mismatch.

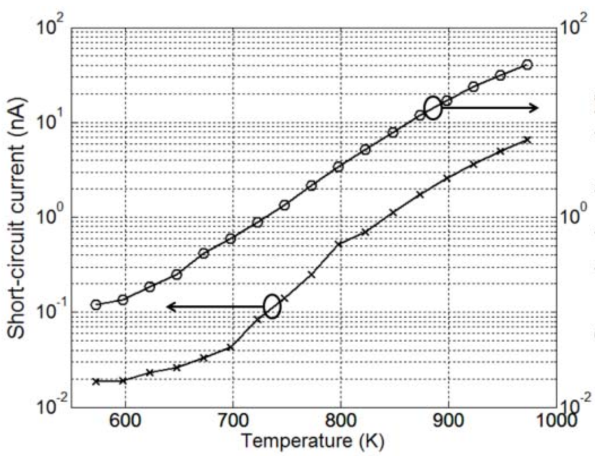

Fig. 2. Rectenna short-circuit current I_{SC} and open-circuit voltage V_{OC} as a function of the source temperature T_A. The rectenna temperature T_D was maintained at a constant temperature of approximately 296 K.

The maximum power that can be converted by a single rectenna is too low to be used in practical applications. The theoretical limit determined by (1) assuming Carnot's efficiency is approximately 280 nW at 973 K. The overall power extraction can however be increased to useful levels by fabricating a rectenna array. The finite size of the antenna limits the power at low frequencies, but enables a larger number of rectennas on the same area. If we assume that the footprint of a rectenna occupies an area $L \times L$, and that the low-frequency cutoff scales with $1/L$ it is beneficial to operate the rectennas with a narrow bandwidth close to the quantum cutoff of the thermal source PSD at kT_A/h. Numerical simulations accounting for the actual rectenna characteristics are necessary to determine the optimum antenna dimensions [5]. The optimum size results in a maximum available power approaching the prediction of the Stefan-Boltzmann law.

III. Conclusions

Here we have demonstrated the operation of a rectenna based on the SSD for converting radiant thermal energy to useable dc power. The measured efficiency of 0.02% was mainly limited by the impedance mismatch between the antenna and the SSD. Our current work aims to characterize the reflection coefficient and to design compact matching network. Large rectenna array have also been fabricated and their application in commercial energy recovery system integrated in exhaust pipes is currently investigated with support from companies in the automotive sector.

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